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Aero-Elastic Optimization of a 10 MW Wind Turbine

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Publication date:
2015

Document Version
Peer reviewed version

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IQPC Workshop for Advances in Rotor Blades
for Wind Turbines
24-26 February 2015
Bremen, Germany

DTU Wind Energy
Department of Wind Energy

Design Challenge

What are the multidisciplinary trade-offs between rotor mass and AEP for a 10 MW rotor mounted on the DTU 10MW RWT platform?

Introduction
This Talk

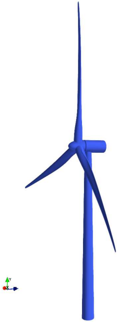
Design Challenge

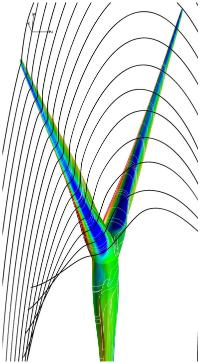
What are the multidisciplinary trade-offs between rotor mass and AEP for a 10 MW rotor mounted on the DTU 10MW RWT platform?

- DTU 10MW Reference Wind Turbine,
- Optimization cases:
  - Structural optimization of the rotor,
  - Aero-structural optimization of the rotor,
  - Fatigue constrained aero-structural optimization of the rotor,
  - Frequency constrained aero-structural optimization of the rotor.
- Conclusions.

Previous Work
The DTU 10MW Reference Wind Turbine

- Fully open source, available at http://dtu-10mw-rwt.vindenergi.dtu.dk,
- Detailed geometry,
- Aeroelastic model,
- 3D rotor CFD mesh,
- Detailed structural description, ABAQUS model,
- 300+ users,
- Used as reference turbine in the EU projects INNWIND.eu, MarWint, and IRPWIND, among others.





Previous Work
The DTU 10MW Reference Wind Turbine

Parameter	Value
Wind Regime	IEC Class 1A
Rotor Orientation	Clockwise rotation - Upwind
Control	Variable Speed
	Collective Pitch
Cut in wind speed	4 m/s
Cut out wind speed	25 m/s
Rated wind speed	11.4 m/s
Rated power	10 MW
Number of blades	3
Rotor Diameter	178.3 m
Hub Diameter	5.6 m
Hub Height	119.0 m
Drivetrain	Medium Speed, Multiple-Stage Gearbox
Minimum Rotor Speed	6.0 rpm
Maximum Rotor Speed	9.6 rpm
Maximum Generator Speed	480.0 rpm
Gearbox Ratio	50
Maximum Tip Speed	90.0 m/s
Hub Overhang	7.1 m
Shaft Tilt Angle	5.0 deg.
Rotor Precone Angle	-2.5 deg.
Blade Prebend	3.332 m
Rotor Mass	227,962 kg
Nacelle Mass	446,036 kg
Tower Mass	628,442 kg
Airfoils	FFA-W3

Table: Key parameters of the DTU 10 MW Reference Wind Turbine.

Case 1: Pure Structural Optimization with Fixed Outer Shape

Minimise (Case 1a)	$-\frac{M_{blade-ref}}{M_{blade}}$
Minimise (Case 1b)	$-\frac{Mmom_{blade-ref}}{Mmom_{blade}}$
with respect to	$x = \{t_{mat}, DP_{caps}\}$ (47 dvs)
subject to	Constraints on: Tip deflection at rated power, Tip torsion at rated, Extreme wind tip deflection, Ultimate strength, Basic spar cap buckling: $t_{cap}/w_{cap} > 0.08$, $\frac{P_{mek}}{P_{mek-ref}} > 1.$ $\frac{T_{max}}{T_{max-ref}} < 1.$

- HAWCStab2 load cases: 7 operational cases, 1 extreme 70 m/s 15 deg yaw error
- 5 pre-computed extreme load cases for stress analysis.

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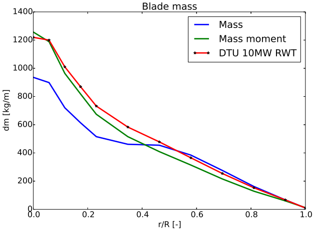
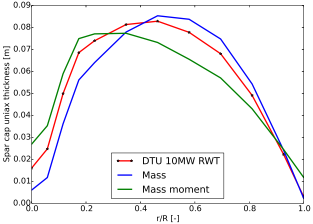
Case 1: Mass Distribution

- Minimization of either mass or mass moment results in drastically different designs.
- Mass minimization: 17% reduction in mass, 0.6% increase in mass moment,
- Mass moment minimization: 9% reduction in mass, 13% reduction in mass moment.
- Mass minimization tends to remove mass primarily from the inner 50% span.
- Mass moment minimization removes mass more evenly, which will contribute to a reduction in fatigue.





Case 2: Shape and structural Optimization for Mass and AEP

Minimise	$-\left(w_{pow} * \frac{AEP}{AEP_{ref}} + (1 - w_{pow}) * \frac{M_{blade-ref}}{M_{blade}}\right)$
For cases	w_{pow} = [0.8, 0.85, 0.9, 0.925, 0.95, 0.975]
with respect to	$x = \{c, \theta, t_{blade}, t_{mat}, DP_{caps}\}$ (56 dvs)
subject to	Constraints on: Tip deflection at rated power, Tip torsion at rated, Extreme wind tip deflection, Ultimate strength, Basic spar cap buckling: $t_{cap}/w_{cap} > 0.08$, $T_{rated} < T_{rated-ref}$, $T_{extreme} < T_{extreme-ref}$, Extreme blade flapwise load $<$ ref value Extreme blade edgewise load $<$ ref value

- HAWCStab2 load cases: 7 operational cases, 1 extreme 70 m/s 15 deg yaw error
- 5 pre-computed extreme load cases for stress analysis.

Results

Case 2: Pareto Optimal Designs

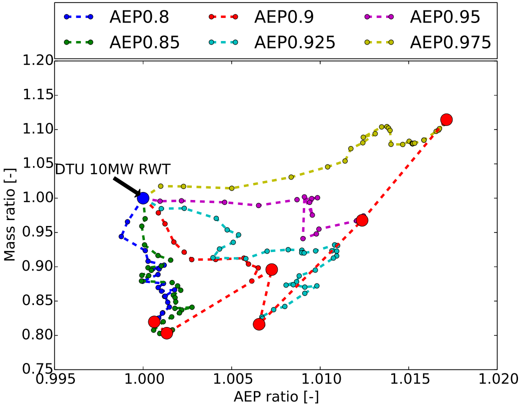
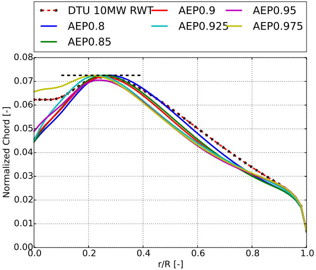
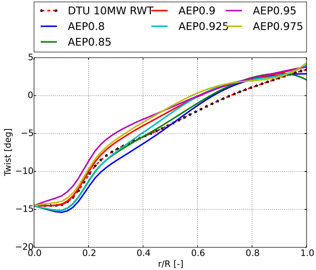


Figure: Pareto optimal designs for the massAEP cases.

Case 2: Blade Planform

- All designs tend towards a more slender chord distribution, and a significant reduction in root diameter.
- Maximum chord constraint is active.





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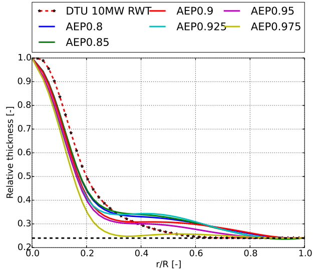
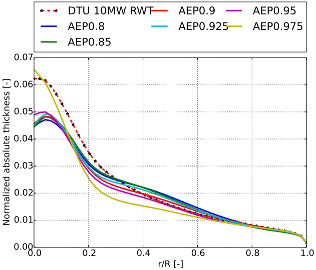
Case 2: Blade Planform

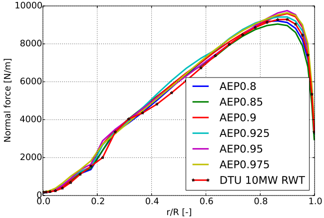
- All designs tend towards a more slender chord distribution, and a significant reduction in root diameter.
- Maximum chord constraint is active.
- Significant increases in relative thickness mid-span in particular for the mass-biased designs.
- Absolute thickness lower in root and higher midspan.

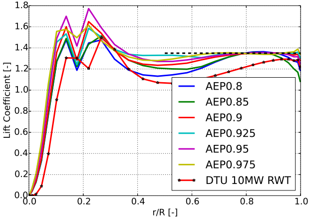




Case 2: Aerodynamic Performance at 10 m/s

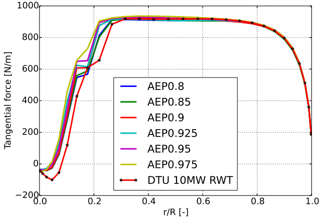
- Mass biased designs tend towards unloading the tip.
- Slender design requires higher operational lift coefficients
- $Cl - max$ constraint active for all designs.

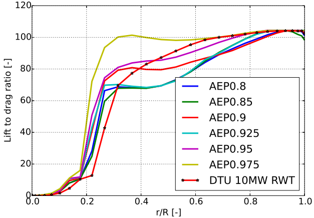




Case 2: Aerodynamic Performance at 10 m/s

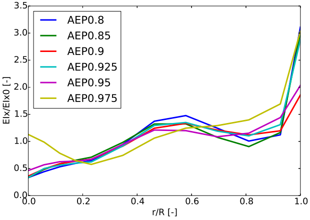
- Mass biased designs tend towards unloading the tip.
- Slender design requires higher operational lift coefficients
- $Cl - max$ constraint active for all designs.
- Increase in thickness compromises performance mid-span.
- Increase in performance on inner part of blade due to reduction in thickness.

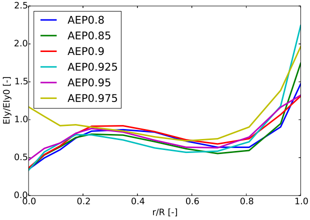


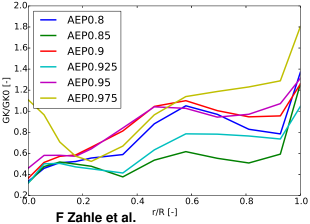


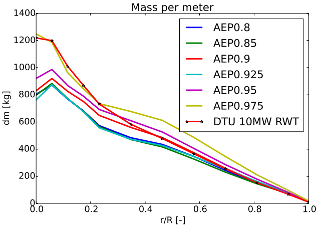
Results

Case 2: Structural Characteristics









Case 2: Structural Characteristics

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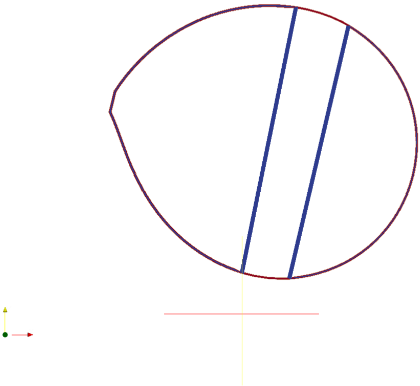
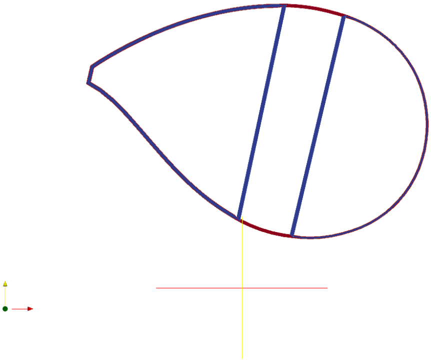
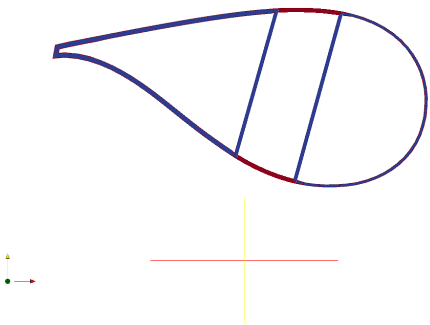


Results

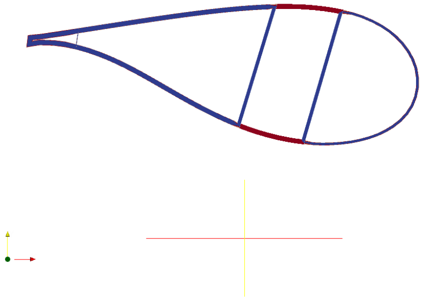
Case 2: Structural Characteristics



Results
Case 2: Structural Characteristics



Results
Case 2: Structural Characteristics



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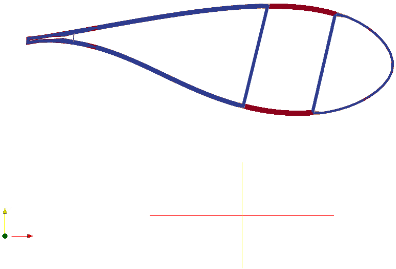
Results

Case 2: Structural Characteristics



Results

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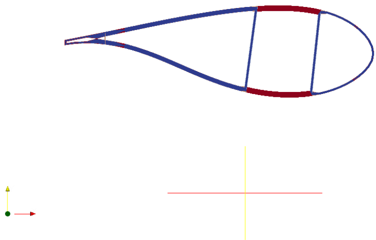

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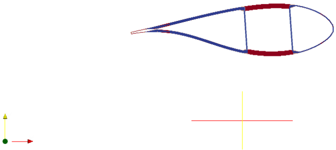
Results
Case 2: Structural Characteristics



Results

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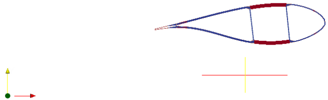

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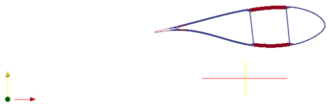

Case 2: Structural Characteristics

Results

Case 2: Structural Characteristics

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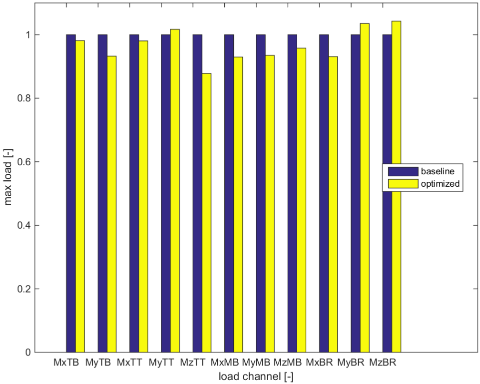
Results

Case 2: Extreme Loads Computed Using HAWC2



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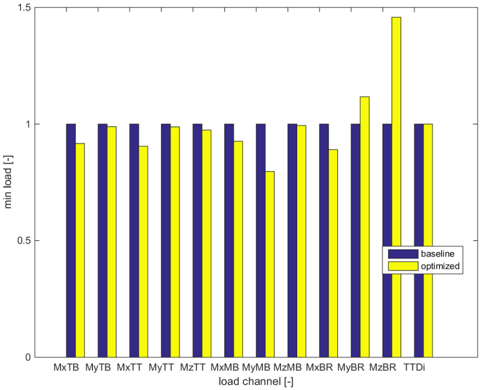
Results

Case 2: Extreme Loads Computed Using HAWC2



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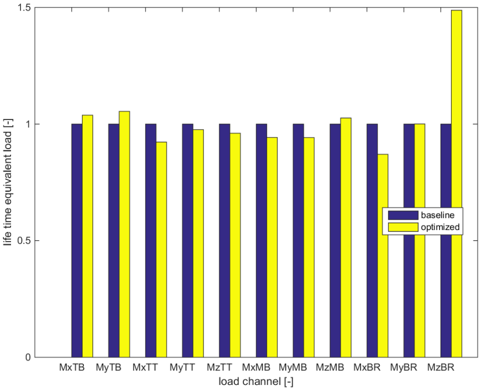
Results

Case 2: Extreme Loads Computed Using HAWC2



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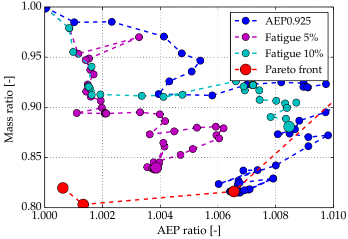
Case 3: Shape and structural Optimization with Fatigue Constraints

Minimise	$-\left(w_{pow} * \frac{AEP}{AEP_{ref}} + (1 - w_{pow}) * \frac{M_{blade-ref}}{M_{blade}}\right)$
with	$w_{pow} = 0.9$
with respect to	$x = \{c, \theta, t_{blade}, t_{mat}, DP_{caps}\}$ (56 dvs)
subject to	Constraints on: Tip deflection at rated power, Tip torsion at rated, Extreme wind tip deflection, Ultimate strength, Basic spar cap buckling: $t_{cap}/w_{cap} > 0.08$, $T_{rated} < T_{rated-ref}$, $T_{extreme} < T_{extreme-ref}$, Extreme blade flapwise load $<$ ref value Extreme blade edgewise load $<$ ref value Tower bottom long. fatigue $<$ [5%, 10%] Blade rotor speed fatigue $<$ ref value

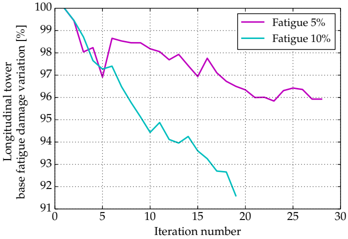
- HAWCStab2 load cases: 7 operational cases, 1 extreme 70 m/s 15 deg yaw error
- 5 pre-computed extreme load cases for stress analysis.

Case 3: Pareto Front

- Fatigue constrained designs lie inside the pareto front of the massAEP designs.
- Both the 5% and 10% fatigue constraint almost met.
- Optimizations not fully converged.



a) AEP and blade mass in the Pareto front.



b) Tower base longitudinal bending moment fatigue damage variation.

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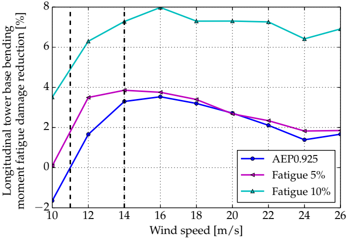
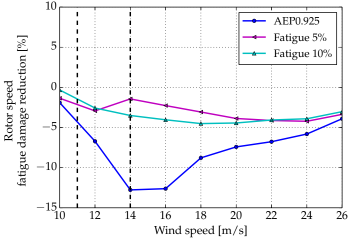
Results

Case 3: Validation of Results With Time Domain Simulations

- Fatigue damage equivalent load reduction of tower base longitudinal bending moment and rotor speed with respect to the reference design.
- Values evaluated with nonlinear time domain simulations.
- Dashed vertical lines indicate the wind speed where the constraint is present in the optimization.





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Case 4: Shape and structural Optimization with Frequency Constraint

Minimise $-\left(w_{pow} * \frac{AEP}{AEP_{ref}} + (1 - w_{pow}) * \frac{M_{blade-ref}}{M_{blade}}\right)$

with $w_{pow} = 0.9$

with respect to $x = \{c, \theta, t_{blade}, t_{mat}, DP_{caps}\}$ (56 dvs)

subject to Constraints on:
Tip deflection at rated power,
Tip torsion at rated,
Extreme wind tip deflection,
Ultimate strength,
Basic spar cap buckling: $t_{cap}/w_{cap} > 0.08$,
$T_{rated} < T_{rated-ref}$,
$T_{extreme} < T_{extreme-ref}$,
Extreme blade flapwise load $<$ ref value
Extreme blade edgewise load $<$ ref value
abs((Edgewise FW mode frequency)/6P) $>$ 7%
min(Edgewise BW mode damping) $>$ 1%

- HAWCStab2 load cases: 7 operational cases, 1 extreme 70 m/s 15 deg yaw error
- 5 pre-computed extreme load cases for stress analysis.

Results
Case 4: Pareto Front

- The frequency constrained design lies significantly inside the pareto front of the massAEP designs.

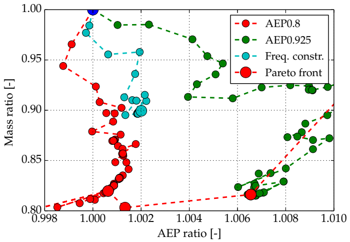

Figure: Iterations of Test case 4 optimizations.

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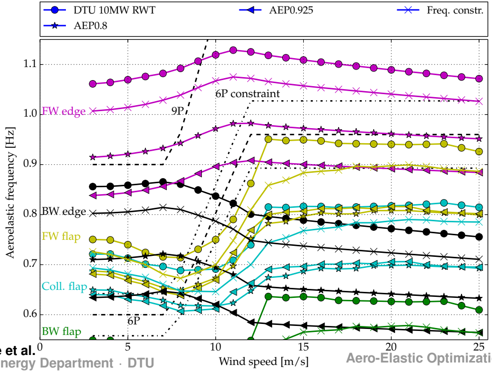
Case 4: Aeroelastic Frequencies

- All aeroelastic frequencies of the optimized designs are reduced.
- The FW edgewise mode of the AEP0.8 design overlaps the 6P frequency, while the AEP0.925 is sufficiently below.
- The frequency constrained design hits the upper frequency constraint at 25 m/s.



Conclusions

- Multi-disciplinary trade-offs between mass reduction and AEP successfully captured by the fully coupled MDO approach,
- Significant reductions in mass and increase in AEP, depending on the weighting of the cost function.
- New frequency based model for fatigue showed promising results with up to 8% reduction in tower bottom longitudinal fatigue.
- Frequency placement was demonstrated, although the constraint formulation resulted in less improvements in the design than the unconstrained designs.

Ongoing/Future Work

- In progress: Further design of 10 MW rotors with the Risø airfoil series,
- Additional extreme load cases?
- Further tuning of necessary constraints.
- Buckling: Buckling loads are not computed, which is an important design driver. Low fidelity methods suitable for optimization need to be implemented.
- Bend twist coupled blades,
- Blades with trailing edge flaps.
- Implementation of CoE models based on FUSED-Wind.